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A demand scenario based fuelwood supply chain: A conceptual model

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ABSTRACT

Fuelwood is one of the main fuels for heating in many countries. As the price of fuelwood is relative low, comparing to oil or gas, demand for fuelwood rises over the years. A supply chain is considered by different nodes that are essential for some operations concerning transportation and production. Due to the sensitive nature of the forest, which is the "production plant" in the examined supply chain, certain restrictions concerning the production and distribution of fuelwood should be taken into account. A more environment oriented production model should be developed taking into consideration the sustainable management of the forests. For this purpose a mixed integer linear programming (MILP) model is considered in modeling uncertainty for fuelwood demand. Moreover, the minimization of the overall operations cost is examined under different fuelwood demand representations using Lagrangean relaxation algorithm.

Contents

1. Introduction

The global interest in dealing with the energy crisis and securing the energy supply has led to the promotion of renewable energy sources (RES), in various sectors of the economy [1].

RES can improve the variety of supply in energy markets, reducing thus the dependence on oil; they can also help to safeguard sustainable energy sources on a long-term basis, and contribute to a reduction of the local and global environmental impact on regional sustainable development. RES account for 17% of the global primary energy production, mainly through large hydroelectric installations and the use of traditional types of forest biomass and agricultural residues in developing countries [2].

The sustainable management of biomass necessitates an improved rate of exploitation of natural resources, avoiding the depletion of natural carbon deposits. In recent decades, a

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disquieting increase of carbon dioxide has been observed in the environment, while at the same time, its deposits are constantly decreasing due to the extensive destruction and degradation of natural ecosystems. This fact also contributes to the atmospheric pollution of the environment and intensifies climate change [3].

The use of biomass as a low cost form of energy could be further expanded. However, the absence of a sound energy policy aggravates the market situation and puts forward significant economic obstacles, which render biomass non-competitive vis-à-vis other renewable energy forms and fossil fuels. There would be no economic difficulties for the promotion of biomass, if a strong policy was put into place that would promote its use, and differentiate it from the remaining RES. What is required is the implementation of a rational policy that would promote biomass use on the global market [4].

2. RES and the use of fuelwood

Fuelwood is one of the main types of biomass and its contribution to the energy requirements of a country is significant [5,6].

The energy policies of various countries differ depending on the needs of each country and their level of dependence on fossil fuel imports. Low-income families cannot afford the costs that the use of fuel and the purchase of new technological products entail. Therefore, an alternative energy policy based on the reduced use of fuelwood cannot be promoted in such countries [7].

The energy policy objectives been defined by developed countries favour the use of RES only for the production of electricity and biofuel. Minimum efforts have been made to promote the use of fuelwood. The only exception is the widespread use of fuelwood in rural areas. Only in recent years, have efforts been observed by state authorities to provide the necessary funding for its promotion. However, given the fact that the relevant funding is minimal, no major tax incentives have been instituted [8].

The existence of a strategic plan to support renewable energy sources would render fuelwood more competitive in the marketplace, and increase its level of usage compared to other heating sources; nevertheless, this would only be feasible if the price of fuelwood were lower compared to fossil fuel [8].

Fuelwood is a product that is mainly known for its use as a heating source. In many places, beyond its essential part in domestic consumption, fuelwood is used in a broad range of small businesses (bakeries, restaurants etc) at a ratio of 20% of the total consumption [9]. Fuelwood usage depends on the quality and type of wood, its availability in the natural environment and the social characteristics of the populations using it [10]. As an energy source, it has the ability to provide a significant percentage of the energy required by low income rural families and to ensure a low production cost for the urban energy as well. Whether this goal is achieved or not, depends directly on the support of local authorities [1].

The use of energy from biomass and specifically from fuelwood is even today very closely related to the people's quality of life in the rural areas of Africa and Asia. Even in countries such as South Africa, in which an extensive electrification programme has been implemented, wood is still the most widespread type of fuel used for cooking [11].

In countries such as Bangladesh, and more specifically in its rural regions, biomass is the primary energy source for households. In order to cover their energy requirements, household owners mainly collect bamboo, branches, cow dung, fuelwood, rice husk, leaves, twigs and straw [12].

In addition, wood is still the type of fuel chosen by most urban households in the capital of Burkina Faso. The demand for energy from wood is directly linked to household income. The percentage of fuelwood usage decreases as household income rises [13].

In an area of Uganda, it was found that there is almost full dependence on the use of fuelwood for household cooking and for small industries. Most of the fuelwood for household use is collected by women and is mainly dead wood, resulting thus in a limited environmental impact on forest ecosystems [14].

In Greece the energy consumption is expected to rise significantly over the next few years, since it is considered essential for the country's economic growth, if it is to cover the gap that separates it from the developed economies of the European Union [15].

The country however is dependent to a large extent on the import of oil and natural gas. The increased energy requirements of Greece cause significant problems to the balance of payments, with a further impact on the other macro-economic figures of its economy [15]. There is therefore a need to further intensify the exploitation of domestic energy sources, and particularly RES.

The share of RES in the national energy balance is around 5.6% of the total gross domestic consumption and 17.7% of the domestic primary energy production. In 2008, the production of primary energy from RES was 1.8 Mtoe, compared to 1.2 Mtoe in the early 1990s. Of these, 600 ktoe approximately are attributed to the use of biomass in households and 264 ktoe to the use of biomass for industrial needs [16].

Although the overall contribution of RES to the gross domestic energy consumption is relatively low (5.5–6.5%) the contribution of RES other than household consumed biomass and large hydroelectric plants is presenting a steady increase due to measures targeted to its economic support [16].

In Greece, the primary energy form of biomass is the wood produced by Greek forests, which is mainly used as fuel by households. Agricultural crop residues constitute also an important and promising biomass source (branches, straw etc).

Greek forests and other forest areas produce a range of products and services [17,18]. Fuelwood is one of the primary products of Greek forests, since it accounts for over 65% of the total wood production in recent years [19,20]. The production of fuelwood mainly comes from oak forests, which cover a large part of Greece [21]. In recent years, there has been a shift in European Union policies regarding the development of rural areas (agro-environmental measures, LEADER+ etc), which has opened up new opportunities for the exploitation of agricultural land by its owners [22,23]. Thus, the plantations of forest species that have been created in abandoned or low productive agricultural lands within the framework of EU policies seem to be in position to contribute to the increase in the produced quantities of fuelwood over the next few years [24].

Total wood production has significantly decreased in recent decades (from 1.7 million m^3 in 1990 to 0.96 million m^3 in 2007 [25]). This reduction had largely affected fuelwood compared to industrial wood [26], due to the much better prices paid to loggers for the sale of industrial wood. However, the economic crisis of recent years lowered the demand of industrial wood and increased the demand for fuelwood; nowadays significant quantities of even industrial wood are being sold to households as fuelwood.

In the past, the consumption of fuelwood was very high in rural areas, particularly those located in mountainous and semi-mountainous parts of the country. Its consumption had gradually decreased following the reduction of rural population (due to urbanism), the improved standards of living and the substitution of fuelwood with other fuel, primarily oil. However, the oil crises and the use of fireplaces in urban residences and country houses, had contributed somewhat to an increased demand for fuelwood [26,27]. Today, due to the economic crisis affecting the country, the consumption of fuelwood has increased in a number of households, mainly those situated in rural areas [28].

[Forests in Greece, according to the latest census, cover 33,58,000ha or 25.4% of the country's total area. Approximately

2/3 or 65.4% belong to the state and the remaining 34.6% are not state-owned, and belong to private entities, Local Authorities, monasteries and other public benefit organizations [29]. The body responsible for the exploitation of forests is their owner as a rule. Therefore, the body responsible for the exploitation of public forests is the Greek state. Until the end of 1986, two systems for the exploitation of public forests were used in Greek forestry. One was the self-supervision system, within the framework of State Forest Exploitation (KED, from the Greek acronyms) by the local Forest Services [18], according to article 137 of L.D. 86/69, and the other was through the leasing of the forest's production (timber cut) by forest cooperatives, according to article 134 of L.D. 86/69 or following an auction among those interested in leasing, according to article 120 of L.D. 86/69 [18,30].

Through the first system, the Public (Forest Service) carries out the exploitation of forests by assigning their logging to the Forest Cooperatives, who are paid according to the timber produced. According to the second system, the Public leases the production to Forest Cooperatives, who pay a lease depending on the volume of the timber expected to be produced, and then sell the wood products themselves.

With article 74 of L. 1541/85 and of P.D 126/86, a new system of exploitation (the third) was introduced for the exploitation of public forests, according to which the exploitation of forests is assigned to Agricultural Forest Cooperatives, who pay a percentage of the selling price of forest products to the Central Fund for Agriculture, Livestock and Forests and to the Local Authorities, within whose administrative boundaries the specific forest, forest part or stand is situated [18,30].

In this paper a production–allocation model is presented for the optimal management of fuelwood in Greece. The need of a production management model that would incorporate both environmental and economic criteria is more imperative now, due the rapid increase in fuelwood demand. In a fuelwood supply chain, the “factory” is considered to be the forest. Through the channels of the supply chain (AFCs and fuelwood merchants) the product arrives at the customer (households, industries etc). Fuelwood production and demand are linearly dependent, so when there is an increase in demand, the production should be also increased, so as to cover the demand. Increased fuelwood production affects the sustainability of the natural resource, leading to irreversible situations. The proposed model, which is an extension of [31], incorporates the restrictions posed by legislation (P.D. 126/86) on the maximum produced fuelwood quantities, minimizing the overall cost (production, transportation, and fixed installation cost of the warehouses).

The rest of the paper is organized as follows: In Section 3 the problem statement and the proposed mathematical formulation are presented and discussed and in Section 4 expected results and further research on the proposed model are presented.

3. Mathematical formulation

3.1. The fuelwood supply chain

The fuelwood supply chain (FSC) is quite similar to this of a common product but with a few changes. Examining the supply chain in a general form several nodes are considered. A FSC is very important to rural development and can be characterized as a form of local bioenergy system (LBES) [32]. At the beginning of the supply chain there are the production plants, the units that combine all the raw material for the manufacture of the product. The next step after production is to transport the product to an intermediate node that is used for storing and for distributing the product to the customers, depending on the demand. In the final stage of the supply chain there are the customers whose demand must be satisfied [33]. In order for the companies to achieve the best level of customers' service they try to improve not only the design of the supply chain (SCD) but also the supply chain operations (SCO) conducted amongst the different nodes. In the present case the above formulation can be used with a few changes. Each company depending on the nature of the product and on the structure of its supply chain considers one of the following supply chain models: the pull or the push systems [34]. The first systems are also known as centralized systems, as central decisions are made about the produced quantity. In a centralized system the production is planned without taking into consideration the demanded quantity of the product. This production policy may lead to overbalance of the demanded quantity. The latter production systems, also called decentralized, adjust the produced quantity according to the information brought from the customers' demand. These systems adopt built to order (BTO) policies and can be well fitted to computers or car production systems.

The first step in setting up a FSC is to replace the production plants with forests, which are the production “facilities” for the chain. Due to the fact that a forest has a limited produced quantity and a limited time horizon for the cutting, a pull system for the FSC can be adopted. Each forest is divided, for managerial reasons, into forest compartments. The compartments to be exploited each year, according to the management plan, are assigned to Agricultural Forest Cooperatives (from now on AFCs) following the regulations of laws mentioned previously. AFCs are located into villages inside or in the vicinity of the forest. The wood of felled trees is not formulated into fuelwood at the forest compartments, but it remains in the form of relative long logs for cost effective transportation. The produced quantity in this form is directly sold by the AFCs to fuelwood merchants, which in turn cut it into small logs appropriate for consumption and sell it to customers. Facilities of the AFCs and merchants are considered already installed with a given capacity. The amount of fuelwood demanded from the AFCs and the merchants is complementary. Quantities of fuelwood are considered to be delivered to customers' zones which represent large areas, as villages or cities. The demand for fuelwood is estimated in advance, based on statistical data from previous years. The examined FSC is presented in Fig. 1.

Main objective of the study is the minimization of the total cost of the processes occurring in the FSC. As the proposed model is demand driven (when demand increases the supply should rise at appropriate levels to cover the demand) an increase would lead to overall increase of the quantities produced and therefore to the overall cost. Thus, in order to avoid forest degradation and over logging that rapid changes in fuelwood demand may create, the fuelwood quantities produced are assumed to be upper and lower bounded. Due to the large distance between merchants and customers and the specific conditions for fuelwood maintenance (to guarantee low moisture and easy and effective combustion) intermediate warehousing facilities located at merchants' sites are also assumed. For this purpose a mixed integer linear

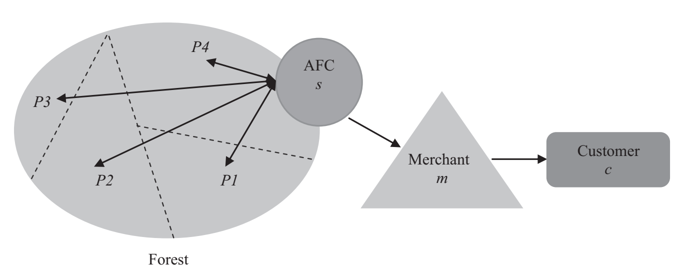

Fig. 1. The examined FSC.

programming (MILP) model is examined providing information about the following processes throughout the planning horizon of the considered FSC:

- The fuelwood volume produced.
- The levels of wood transported from AFCs to fuelwood merchants.
- The levels of wood transported from merchants to customers.
- The size of warehouse, where fuelwood is stored.
- Location and number of warehousing facilities.
- The total cost of all the processes of the examined FCS.

With the proposed MILP model, decisions about the production, distribution, storage of just fuelwood quantities are proposed, with the use of Lagrangean relaxation algorithm. The model is oriented towards the Greek P.D 126/86 for forest production management (such model has not yet been proposed for production management in Greece). Moreover, due to the fact that any changes in fuelwood demand are incorporated in the proposed model, an overall picture about the cost of the operations conducted and the levels of quantities produced and distributed throughout the supply chain are also derived. Through the use of algebraic formulation the previous structure can have multiple echelons at each stage of the examined FSC. This provides to the proposed model a more realistic approach to the real world problems (Tables 1–4).

Table 1
Indices and sets.

$p \in P$	Forest compartment
$f \in F$	Forest
$s \in S$	AFC
$m \in M$	Merchant
$c \in CU$	Customer
$i \in SC$	Scenario

Table 2
Continuous and decision (binary) variables.

Q_{pfs}	Quantity of fuelwood logged at compartment p of forest f by AFCs (m^3)
P_{fs}	Cumulative quantity of fuelwood logged of all compartments of forest f by AFC s (m^3)
F_m	Quantity of fuelwood processed at merchant's node m (m^3)
Q_{sm}	Quantity of fuelwood sent from AFC s to merchant m (m^3)
Q_{mc}	Quantity of fuelwood sent from merchant m to customer c (m^3)
W_m	Capacity of warehouse installed at merchant's location m (m^3)
Y_m	1 if warehouse m will be installed in merchant's m position, 0 otherwise.
X_{mc}	1 if the connection between merchant m and customer c exists, 0 otherwise.

3.2. Forest production constraints

At the initial stage, there is the forest that is the productive unit of the supply chain. The land use should be subjected to strict constraints regarding sustainable management and conservation of the environment [35]. Fuelwood productive forests are regulated even-aged forests, which are managed under a sustainable framework to ensure their long term productive, protective and environmental services. Therefore, restrictions to the harvesting quantities from each forest stand are set by the management plan in order to both maintain the productive ability of the forest and sustain its non-timber functions. All quantities mentioned below are considered to be converted from stacked cubic meters (*st* m^3) to true cubic meters (m^3) following the next conversion: 1st $m^3 = 0.6\ m^3$.

Let Q_{pfs} be the continuous variable that represents the amount of wood harvested from compartment p of the forest f from AFC s. The quantity harvested from each partition is bounded between an upper (Q^U_{pfs}) and a lower (Q^L_{pfs}) amount. This leads to the following constraints:

$$Q_{pfs} \le Q^U_{pfs}, \ \forall p, f, s \tag{1}$$

$$Q_{pfs} \ge Q^L_{pfs}, \ \forall p, f, s \tag{2}$$

Consequently the quantity harvested from all the forest's compartments would yield the production of fuelwood of forest f. This amount is represented by the continuous variable P_{fs} and models the amount that will be transported through the channels of the FSC and will be finally delivered to the last node, the customer. Hence the following constraint is introduced:

$$\sum_p Q_{pfs} = P_{fs}, \ \forall f, s \tag{3}$$

Table 4
Cost parameters.

C^{CUT}	Cost of cutting trees. (€/m^3)
C^{MOV}	Cost of moving from forest's compartment to the forest road (€/m^3)
MUN GOV	Fixed tax placed at AFCs according to P.D. 126/86 (€/m^3)
$PURCH$	Purchase value of fuelwood quantity by merchants (€/m^3)
$C^{TR}_{AFC \to M}$	Transportation cost of fuelwood quantity from AFC to merchant (€/m^3)
C^{PR}_M	Processing cost of fuelwood at merchant's node (€/m^3)
$C^{TR}_{M \to C}$	Transportation cost of fuelwood from merchant to customer (€/m^3)
C^{IN}_m	Fixed installation cost of a warehouse to merchant's location (€)
$TCFSC$	Total cost of the examined fuelwood supply chain (FSC) (€)
$ETCFSC$	Expected total cost of the examined fuelwood supply chain (FSC) (€)

Table 3
Capacity and demand parameters.

Q^U_{pfs}	Upper bound of quantity of wood logged at compartment p of forest f by AFC s according to P.D 126/86 (m^3)
Q^L_{pfs}	Lower bound of quantity of wood logged at compartment p of forest f by AFC s
P^U_{fs}	Upper bound of cumulative quantity of fuelwood logged of all compartments of forest f by AFC s (m^3)
P^L_{fs}	Lower bound of cumulative quantity of fuelwood logged of all compartments of forest f by AFC s (m^3)
Q^U_{sm}	Upper bound of quantity of fuelwood transported from AFC s to merchant m (m^3)
Q^L_{sm}	Lower bound of quantity of fuelwood transported from AFC s to merchant m (m^3)
Q^U_{mc}	Upper bound of quantity of fuelwood transported of merchant m to customer c (m^3)
Q^L_{mc}	Lower bound of quantity of fuelwood transported of merchant m to customer c (m^3)
D_c	Demand for quantity of fuelwood at customer c (m^3)
W^U_m	Upper bound for the capacity of warehouse installed at merchant's location m (m^3)
W^L_m	Lower bound for the capacity of warehouse installed at merchant's location m (m^3)
$\pi_{(i)}$	Occurring probability of scenario i.

Produced quantity is also bounded between an upper (P^U_{fs}) and a lower (P^L_{fs}) amount. The previous bounds can be derived from the summation of the upper and lower bounds of the compartments of each forest as shown in Eqs. (4) and (5):

$$P^U_{fs} = \sum_p Q^U_{pfs}, \forall f, s \tag{4}$$

$$P^L_{fs} = \sum_p Q^L_{pfs}, \forall f, s \tag{5}$$

3.3. Fuelwood balance constraints

The amounts of fuelwood produced at the forest are transferred though the channels of the FSC to the end customer. At the beginning of the supply chain the produced volume of fuelwood from forest f by AFC s, should be equal to the quantity of fuelwood's volume transported by AFC s to merchant m. Let Q_{sm} be the quantity of fuelwood transferred from AFC s to merchant [36]. The previous statement is modeled by the next equation:

$$\sum_f P_{fs} = \sum_m Q_{sm}, \ \forall s \tag{6}$$

From the node of AFC the flows of fuelwood are transported to the customers' zones. So the quantity delivered from AFC s to merchant m should be equal to the quantity delivered from merchant m to customers' zone c. Let Q_{mc} be the continuous variable that represents the quantity of fuelwood delivered from AFC s to customer zone c then the next constraint is introduced:

$$\sum_s Q_{sm} = \sum_c Q_{mc}, \ \forall m \tag{7}$$

As the transportation of quantities of fuelwood from AFCs to merchants is being done with trucks of finite capacity, the delivered quantities cannot exceed the maximum capacity of the trucks (Q^U_{sm}). Moreover the delivery of quantity of fuelwood can be done if the amount exceeds a minimum certain level (Q^L_{sm}). The previous lead to the next constraints:

$$Q_{sm} \le Q^U_{sm}, \ \forall s, \ m \tag{8}$$

$$Q_{sm} \ge Q^L_{sm}, \ \forall s, \ m \tag{9}$$

Fuelwood quantities that reach the merchant's node are appropriately processed in order to ease the customers. The quantity of fuelwood processed at merchant's node (F_m) can be computed with the following constraint:

$$F_m = \sum_s Q_{sm}, \ \forall m \tag{10}$$

The quantity of fuelwood transported from merchants to customers' zones should be equal to the demanded quantity of fuelwood at customer zone c (D_c). The previous can be modeled through the following constraint.

$$\sum_m Q_{mc} = D_c, \ \forall c \tag{11}$$

In merchants' node, the number of warehousing facilities is determined through MILP solution. Let Y_m be a decision (binary) variable, that take a value of 1 if warehousing facility (W_m) will be installed in merchant's m location and 0 otherwise. The possible installed facilities have finite capacity and have an upper and a lower bound. The previous proposition is modeled with the following constraints:

$$W_m \le W^U_m \times Y_m, \ \forall m \tag{12}$$

$$W_m \ge W^L_m \times Y_m, \ \forall m \tag{13}$$

As in constraints (8) and (9), the quantities delivered from merchants to customers should be bounded between a lower (Q^L_{mc}) and an upper (Q^U_{mc}) bound concerning the minimum amount that can be delivered and the maximum capacity of the trucks that are used for the transportation, respectively, and are delivered only if the connection between warehouse m and the corresponding customer, exist. If X_{mc} is a decision variable that represents the connection between merchant's warehouse m and customer c, the next constraints are introduced:

$$Q_{mc} \le Q^U_{mc} \times X_{mc}, \ \forall m, c \tag{14}$$

$$Q_{mc} \ge Q^L_{mc} \times X_{mc}, \ \forall m, c \tag{15}$$

$$X_{mc} \le Y_m, \ \forall m, \ c \tag{16}$$

$$\sum_m X_{mc} = 1, \ \forall c \tag{17}$$

Inequality (16) implies that a connection between the warehouse placed located at a merchant's site would exist if-f warehouse m is installed. Equality (17) implies that each customer c is served by exactly one warehouse m (single sourcing constraint).

3.4. Non-negativity constraints

As all the continuous variables introduced in the previous paragraphs represent quantities of fuelwood, by solving the linear programming problem the resulting values of these continuous variables cannot be negative. Therefore the next non-negativity constraints are introduced:

$$Q_{pfs} \ge 0, \ \forall p, f, s \tag{18}$$

$$P_{fs} \ge 0, \ \forall f, s \tag{19}$$

$$Q_{sm} \ge 0, \ \forall s, m \tag{20}$$

$$Q_{mc} \ge 0, \ \forall m, c \tag{21}$$

$$\begin{array}{l} F_m \ge 0, \ \forall m \\ W_m \ge 0, \ \forall m \end{array} \tag{22}$$

3.5. Objective function

As main objective of the proposed mathematical model is to minimize the total cost of the operations of FSC, in this section the terms of the objective function will be analyzed.

The forest is considered the first link of the examined FSC and different compartments of the forest are exploited by AFCs. Let C^{CUT} represent the cost of cutting the trees and C^{MOV} of moving the trees from forest's compartment to the forest road. The overall cost of the previous operations is modeled with the next term:

$$(C^{CUT} + C^{MOV}) \times \sum_p \sum_f \sum_s Q_{pfs} \tag{23}$$

As mentioned above the total amount of fuelwood logged from all compartments of a forest is equal to the amount of fuelwood that is produced from the forest. According to P.D 126/86, a tax is placed on AFCs for the exploitation of the forest. A part of this tax is attributed to the municipality where the forest geographically belongs to (MUN), another part is attributed to the government (GOV). Based on the above, the next term is introduced in the objective function:

$$(MUN + GOV) \times \sum_f \sum_s P_{fs} \tag{24}$$

The next link after AFCs is the merchants who purchase the logged quantity from AFCs. Here also a variation of operations is done regarding transportation, and cutting the pieces in smaller ones. Let $PURCH$ be the purchase cost of logged amount of

merchants from AFCs and $C^{TR}_{AFC\to M}$ be the cost of transporting the quantity of fuelwood from AFCs to merchants. So the next term is introduced in the objective function to model the transportation cost:

$$(PURCH + C^{TR}_{AFC\to M}) \times \sum_s \sum_m Q_{sm} \tag{25}$$

At merchant's node one of the operations that are done is the cut of the logged quantity into smaller pieces so that would be easy to use in a household fireplace. If C^{PR}_M denotes the processing cost of the above described operation done at merchant's node then the following term is introduced in the objective function:

$$C^{PR}_M \times \sum_m F_m \tag{26}$$

The final operation at the merchant's node is that of the transportation of fuelwood to the customers. Let $C^{TR}_{M\to C}$ represent the transportation cost of fuelwood quantity from merchants to customers. Thus the following term is introduced in the objective function:

$$C^{TR}_{M\to C} \times \sum_m \sum_c Q_{mc} \tag{27}$$

For the installation of a warehouse facility in a certain location, a fixed installation cost is required. Let C^{IN}_m be the fixed installation cost of the warehousing facility in merchant's location m. The total installation cost is expressed with the following term in the objective function:

$$\sum_m C^{IN}_m \times Y_m \tag{28}$$

The total cost of the examined FSC(*TCFSC*) integrates all the costs of the operations conducted within the chain. Hence the final form of the objective function is derived from the summation of terms (23)–(28).

$$\begin{aligned}\min TCFSC = {} & (C^{CUT} + C^{MOV}) \times \sum_p \sum_f \sum_s Q_{pfs} \\ & + (MUN + GOV) \times \sum_f \sum_s P_{fs} \\ & + (PURCH + C^{TR}_{AFC\to M}) \times \sum_s \sum_m Q_{sm} \\ & + C^{PR}_M \times \sum_m F_m + C^{TR}_{M\to C} \times \sum_m \sum_c Q_{mc} \\ & + \sum_m C^{IN}_m \times Y_m \end{aligned} \tag{29}$$

3.6. Implemented policy for the use of fuelwood

Fuelwood is one of the major fuels for heating of households in Greece, because of its low price, which is among the lowest found in EU countries [37]. Also the rapid drop of the average income per capita and the increase of the heating oil price make fuelwood a growing market in Greece. Of course this may have negative impacts on the management alternatives available for the forest, because as the demand increases, the pressure for higher production quantities should increase as well. Examination, therefore, of different demand situations cannot only lead to conclusions on the size of the market to be developed but also give an estimate of the pressure to be exerted to the forest management.

Consequently, a scenario based linear programming model is adopted in order to integrate the expected changes in fuelwood demand [36]. Each scenario, which corresponds to an increase or a decrease of the fuelwood's demand, is weighted by an occurring probability in the objective function and a superscript *s* is inserted at each continuous variable of the model. Let $D^{(i)}_c$ be the demand of fuelwood under different scenarios, $i = 1, 2, \ldots, SC$. Based on the previous, the scenario based demand is the following $|C| \times |SC|$ table$D^{(i)}_c = [D^{(1)}_c D^{(2)}_c D^{(3)}_c \cdots D^{(SC)}_c]$, where $|\bullet|$ measures the size of set $\bullet$.

Each scenario is considered to be complementary, so the corresponding probabilities should verify the next equation:

$$\sum_i \pi_{(i)} = 1 \tag{30}$$

As continuous variables that concern amount of fuelwood are subjected to the variations of fuelwood demand, a superscript is introduced. So all the continuous variables of the examined model are the following:$Q^{(i)}_{pfs}$, $P^{(i)}_{fs}$, $Q^{(i)}_{sm}$ and $Q^{(i)}_{mc}$. Based on the previous constraint (3) will become:

$$\sum_p Q^{(i)}_{pfs} = P^{(i)}_{fs},\ \forall s, f, i \tag{31}$$

Of course the conception of the different scenarios does not affect only the continuous variables of the model, but also the parameters. Regarding productivity upper bounds, following the management plan of a forest, the quantity of fuelwood exploited by AFCs is given and cannot be exceeded if demand for fuelwood increases. Thus the upper bound parameters for any given scenario *i* are considered constant and equal to:

$$Q^{U,(i)}_{pfs} = Q^U_{pfs},\ \forall p, f, s, i \tag{32}$$

$$P^{U,(i)}_{fs} = P^U_{fs},\ \forall f, s, i \tag{33}$$

Regarding the amounts transported through all nodes of the examined FSC also the upper bounds are not subjected to any changes. This is happening due to the fact that the quantity of fuelwood transported is done by trucks with finite space thus the upper bounds cannot change as demand changes. The previous will lead to the following equations:

$$Q^{U,(i)}_{sm} = Q^U_{sm},\ \forall s, m, i \tag{34}$$

$$Q^{U,(i)}_{mc} = Q^U_{mc},\ \forall m, c, i \tag{35}$$

As costs of the examined FSC are fixed, the objective function measures the expected minimum cost, as each scenario is weighted with a corresponding probability. Thus the new objective function represents the expected total cost of the examined FSC and can be written in the following form:

$$\begin{aligned}\min E(TCFSC) = {} & \sum_i \pi_{(i)} \times \Bigg[(C^{CUT} + C^{MOV}) \sum_p \sum_f \sum_s Q^{(i)}_{pfs} \\ & + (MUN + GOV) \times \sum_f \sum_s P^{(i)}_{fs} \\ & + (PURCH + C^{TR}_{AFC\to M}) \times \sum_s \sum_m Q^{(i)}_{sm} \\ & + C^{PR}_M \times \sum_m F^{(i)}_m + C^{TR}_{M\to C} \times \sum_m \sum_c Q^{(i)}_{mc} \Bigg] \\ & + \sum_m C^{IN}_m \times Y_m \end{aligned} \tag{36}$$

4. Solution approach

The fuelwood supply chain, production–allocation model presented above, is a MILP model. The convex problem consists of objective function (29) and linear constraints (1)-(22). A MILP problem can be formed in its general form as follows:

$$\begin{aligned} & P : \min\ z = f^{\mathrm{T}} y + c^{\mathrm{T}} x \\ & s.t \\ & Ax \ge b \\ & Dy \ge d \\ & x \ge 0 \\ & y \in \{0, 1\} \end{aligned} \tag{37}$$

The Lagrangean relaxation problem (LR_P) of (37), also called Lagrangean dual, has the following forms:

$$LR_P : \min_{u \geq 0} z = f^T y + u^T(b - Ax)$$
$$s.t$$
$$Dy \geq d \tag{38}$$
$$x \geq 0$$
$$y \in \{0,\ 1\}$$

Using Lagrangean relaxation technique feasible solutions are obtained that lead to further minimization of the objective function.

Therefore the following inequality is valid [38]:

$$z_{RMILP} \leq z_{LR_P} \leq z_P \tag{39}$$

From (39) z_{RMILP} represents the value of the objective function of the relaxed MILP problem. Dualizing single sourcing constraint (17) such that:$1-\Sigma_m X_{mc}$, the Lagrangean relaxation problem is the following [39]:

$$\max_{u \geq 0} LR_P = \min\left(TCFSC(x) + \sum_c \left[u(c) \times \left(1 - \sum_m X_{mc}\right)\right]\right)$$
$$s.t \tag{40}$$
$$x \in \wp$$

In problem formulation (41), x represents the variables of the problem and $\wp$ is a set that is formed from constraints (1)–(16).

The steps of Lagrangean relaxation algorithm [40,41], are presented below.

$$\left.\begin{array}{l} \text{Solve } P(\text{Objective function (24), Constraints(1)–(17)}) \\ \text{Upper bound}: L^*,\ \text{Initial value for } u^* \\ \theta_o = 2 \end{array}\right\}\text{Initialization}$$

$$\left.\begin{array}{l} \text{for } j = 0, 1, ..., M \\ \gamma^j = g(x^j) \\ t^j = \frac{\theta_j(L^* - L(u_j))}{\|\gamma^j\|^2} \text{ (Step size)} \\ u_{j+1} = \max\{0,\ u_j + t^j\gamma^j\} \\ \text{if } \|u_{j+1} - u_j\| < \varepsilon \\ \text{Stop} \\ \text{end if} \\ \text{If } \textit{no progress in more than } M' \textit{ iterations} \\ \theta_{j+1} = \theta_j/2 \\ \text{else} \\ \theta_{j+1} = \theta_j \\ \text{end if} \\ j = j+1 \\ \text{end for} \end{array}\right\}\text{Subgradient iterations}$$

In Lagrangean relaxation algorithm presented previously, the following assumptions regarding the initialization of the algorithm are made:

a. The upper bound provided for this algorithm is assumed to be equal to the value of the objective function of the relaxed MILP (RMILP) problem, *P*.
b. The initial value provided for u^* is assumed to be the marginal value of constraint (17).

4.1. Description of the numerical example

In this section a numerical example of the proposed MILP model is exhibited. A medium instance regarding the number of compartments, forests, AFCs, merchants and customers is examined. For this numerical example it is assumed that the area for logging covers two forests. For sustainability reasons, fuelwood is produced from two compartments which are considered to have the right age for logging. Quantities of fuelwood are transported by three AFCs over this area to the four merchants of the example so as to cover the demand. The last link of the FSC is the customers which are not treated as single entities but rather than groups of people in villages of small cities. The proposed model is generic and can be applied to any number of nodes of FSC.

The examined model is in a steady state form (time is eliminated from the model). For this reason, cost values, upper and lower capacity of transported quantities and fuelwood demand, are uniformly distributed and are assumed to represent annual mean values. All the aforementioned values regarding cost, upper and lower bounds, capacity and demand are presented in Table 5. Quantities regarding supply and demand express 1000 m^3.

Table 5
Capacity and cost parameters of the numerical example.

Parameter	Value ($\times$ 1000 m^3)
Q^U_{pfs}	$U[5,000,\ 10,000]$
Q^L_{pfs}	$U[200,\ 500]$
P^U_{fs}	$\Sigma_p Q^U_{pfs}$
P^L_{fs}	$\Sigma_p Q^L_{pfs}$
Q^U_{sm}	$U[5,000,\ 30,000]$
Q^L_{sm}	$U[1,000,\ 1,500]$
Q^U_{mc}	$U[5,000,\ 30,000]$
Q^L_{mc}	$U[500, 1500]$
D_c	$U[10,000,\ 20,000]$
Cost	**Value**
$C^{CUT} + C^{MOV}$	100€/1,000 m^3
$MUN + GOV$	50€/1,000 m^3
$PURCH + C^{TR}_{AFC \to M}$	130€/1,000 m^3
C^{PR}_M	100€/1,000 m^3
C^{IN}_m	100,000€

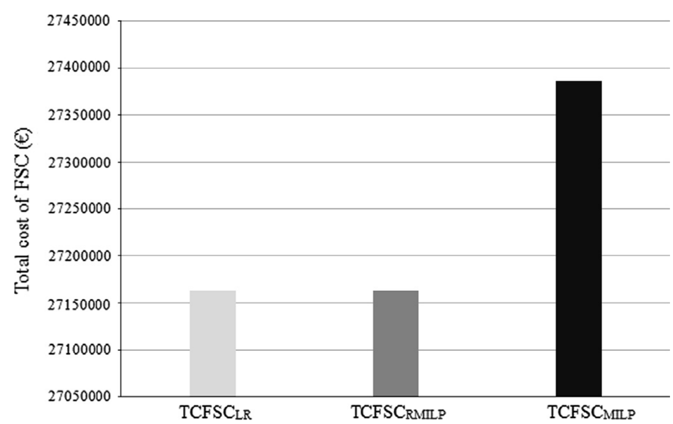

Fig. 2. Total FSC cost for different methodologies used.

4.2. Results

Applying Lagrangean relaxation algorithm to *P*, based on the assumptions made above, the minimum TCSFC cost was obtained after 5 iterations. Fig. 2, presents the overall FSC cost (*TCFSC*) with the use of Lagrangean relaxation algorithm, solving (37) as an MILP and as a relaxed MILP.

From Fig. 2 inequality (39) is valid as the value of minimum cost provided by RMILP, is in this case equal to the value of the objective function using Lagrangean relaxation algorithm. Solving the primal MILP problem, as it can be seen in Fig. 2, yields a

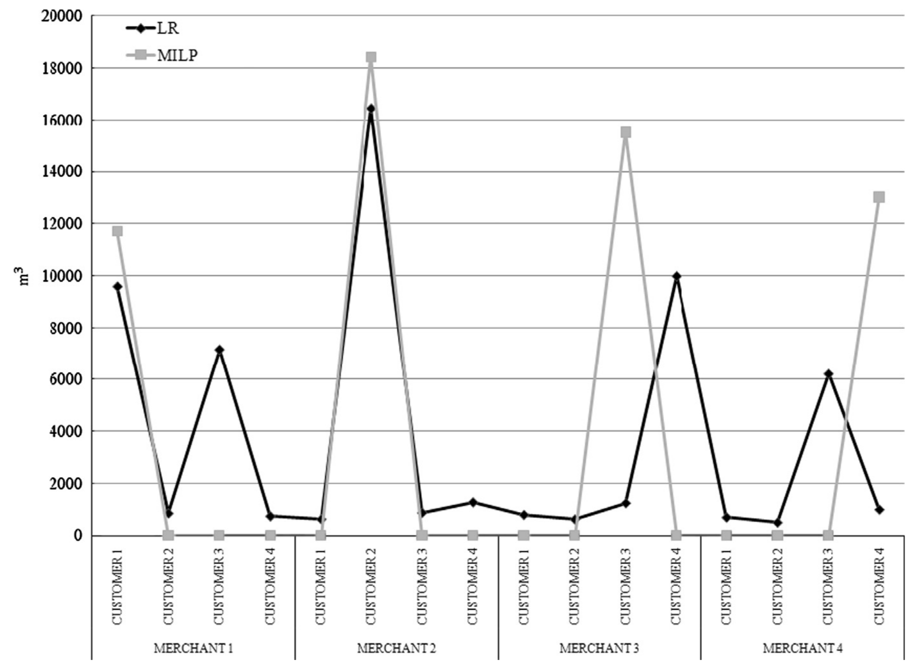

Fig. 3. Solutions of P_{sf} solving problem (37) with and without Lagrangean relaxation algorithm.

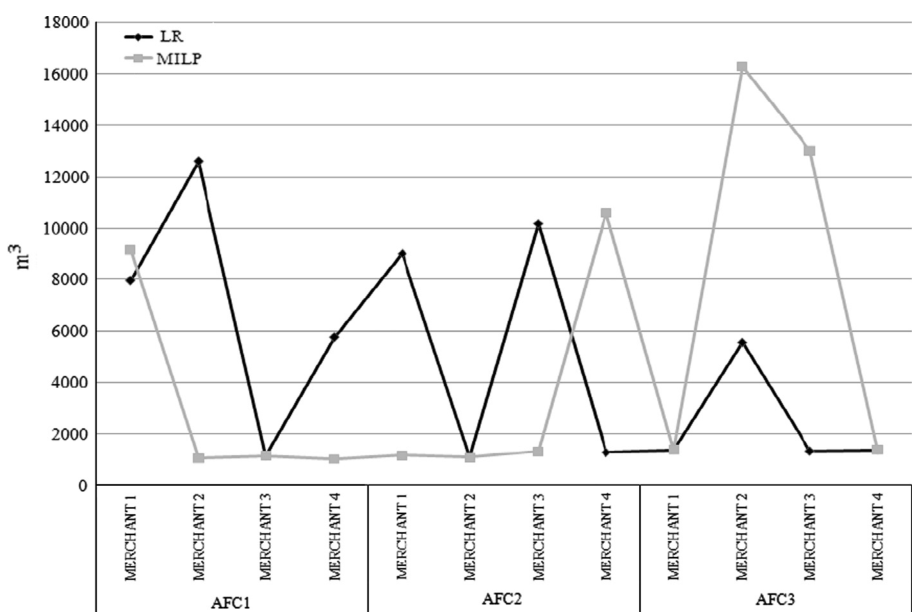

Fig. 4. Solutions of Q_{sm} solving problem (37) with and without Lagrangean relaxation algorithm.

solution which can be further minimized. From the previously methodologies developed, the quantities of fuelwood produced and transported throughout the FSC network is of great interest.

In Fig. 3, the solutions of the problem obtained with the use of Lagrangean relaxation regarding the production of fuelwood from each compartment by AFCs (P_{fs}) show a decreasing but smooth trend. On the contrary, the solutions derived from the primal problem, present large fluctuations which may be more economical in some cases but when dealing with natural resources, sustainability is not guaranteed. The same stands for solutions of variable Q_{sm} that represents the quantities transported from AFC s to merchant m, as it can be seen in Fig. 4. Rapid fluctuations are presented in MILP solution.

In Fig. 5, fuelwood quantities delivered from merchant m to customer c, are presented. The solutions presented in Lagrangean relaxation, show a constant flow of fuelwood from all merchants to all customers, unlike the solutions derived from MILP approach. The previous is attributed to the fact that in the primal MILP model constraint (17) is considered active, while in Lagrangean relaxation algorithm this constraint is dualized and added to the objective function, as stated in problem (39).

4.3. Sensitivity analysis

Due to the nature of the product examined in this work and the rapid increase in demand, several distinct cases of demand representations (scenarios) are examined. At each demand representation a corresponding probability is assigned. Thus the proposed cases are weighted into a single objective. In this case,

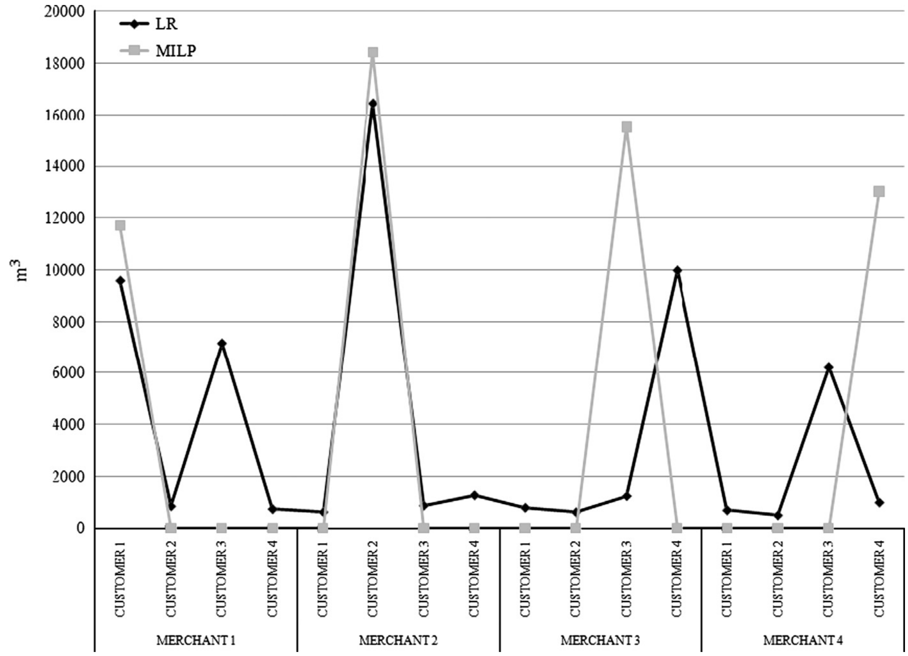

Fig. 5. Solutions of Q_{mc} solving problem (37) with and without Lagrangean relaxation algorithm.

Table 6
Scenarios of increase in demand.

Scenario	Demand increase
1	No increase (D_c)
2	Conservative increase in demand by 50% ($1.5 \times D_c$)
3	Extreme increase in demand by 100% ($2 \times D_c$)

problem (39) is modified as follows:

$$E(TCFSC) = \sum_i \pi(i) \times TCFSC(\mathrm{x}^i) \tag{41}$$

In Table 6, the demand representations are presented. The first scenario states that fuelwood demand will not increase in the future. The second scenario states a quite conservative increase in fuelwood demand by 50%. Finally the third scenario states an extreme increase in demand by 100%.

The choice of weight of each demand scenario was made towards larger fuelwood demands. Let $\pi(1)$, $\pi(2)$ and $\pi(3)$ be the corresponding probabilities of: (a) the current demand, (b) of the conservative increase in fuelwood demand and (c) the extreme increase in fuelwood demand, respectively. Three cases of probability ranges are proposed for this analysis measuring the impact of each demand representation on *TCFSC*:

- $\pi(\bullet,\downarrow) \in (0, 0.15]$, small
- $\pi(\bullet,-) \in (0.15, 0.4]$, medium
- $\pi(\bullet,\uparrow) \in (0.4, 1]$, large

The notation $\pi(\bullet,*)$used for this analysis states that probability corresponding to a demand representation $\bullet$, is weighted with an * impact on objective function. Two distinct set of probabilities are proposed. The first one is$\pi(1,\downarrow)$, $\pi(2,-)$ and $\pi(3,\uparrow)$ which implies that extreme increase is weighted more than the conservative increase while current demand representation is weighted with a small probability. The second one is $\pi(1,\downarrow)$, $\pi(2,\uparrow)$ and $\pi(3,-)$ which implies that the conservative increase in demand is weighted more than the extreme increase in demand, while current situation in fuelwood demand is weighted with only a small probability. In the two aforementioned cases, current situation is weighted with only a small probability as main aim of this analysis is to examine the impact of an increase in demand on *ETCFSC*. Selection of weights is subjected to constraint (30).

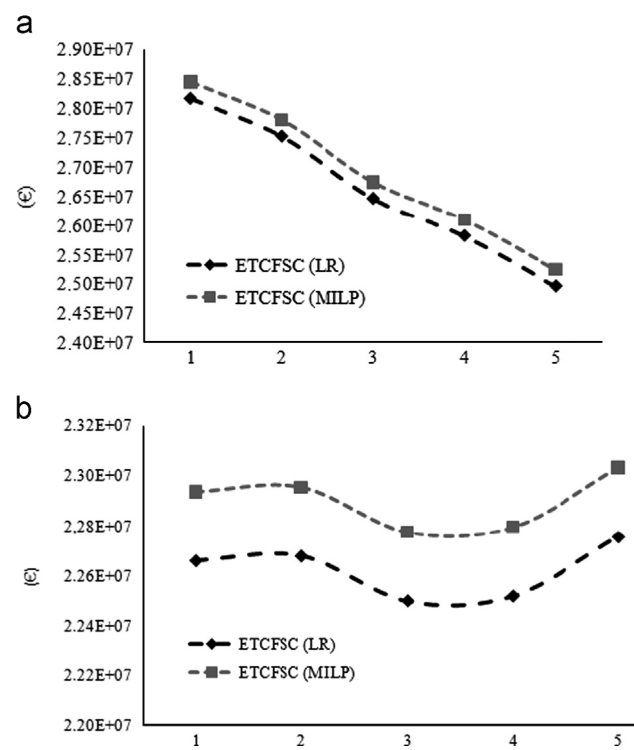

Fig. 6. Cases of scenarios weights on objective function using Lagrangean relaxation (LR) algorithm (grey line) and solving the MILP model without specific algorithm (black line) for: (*a*) $\pi(1,\downarrow)$, $\pi(2,-)$, $\pi(3,\uparrow)$, (*b*) $\pi(1,\downarrow)$, $\pi(2,\uparrow)$, $\pi(3,-)$.

In Fig. 6 a comparative analysis is conducted measuring the reduction of the overall cost of the supply chain, solving the problem without any algorithm (MILP) and using Lagrangean relxation algorithm (LR). As it can be seen in Fig. 6 case (*a*), expected cost has a high value for larger weights placed on

extreme demand increase scenario. As weights on extreme increase scenario decrease, while conservative scenario increases, the expected total cost drops to low levels. In Fig. 6 case (*b*), there is a rapid drop in expected total cost when conservative scenario's probability decreases while extreme scenario's probability increases. Weighting more on the extreme demand increase scenario leads to extreme increases in expected total cost of FSC. For both cases of probabilities sets, it can be seen that the difference between the two costs derived is constant. The solution of the problem with Lagrangean relaxation algorithm yields lower ETCFSC for all of the instances of demand representations and each scenario.

5. Conclusions

Today, the policies of a large number of countries are focusing on energy security and efficiency, particularly those whose dependence on imported energy resources is rapidly increasing.

The European Union encourages and reinforces the valorization of RES, and specifically biomass, for energy production, particularly when it is compatible with its policies in other sectors, such as the common agricultural policy, its environmental policy and regional policy. Even today, several countries continue to use wood as fuel extensively, for heating and cooking.

During the last few years, as a result of the economic crisis in Greece, a consumer preference shift has been observed towards fuelwood. The exploitation of fuelwood contributes to a reduction of the country's dependence on imported fuel, improves its trade balance and saves foreign currency. Therefore, the sustainable management of fuelwood production, the production of high-quality products, the minimization of transportation costs and, in general, of production costs are some of the basic aims of forest farms.

More specifically, an effort is made in this paper to formulate the FSC problem via a MILP model. Lagrangean relaxation algorithm is applied for the solution of MILP problem leading to great minimization of overall cost. As discussed above the model can provide information about the fuelwood quantities that are necessary so as to satisfy an extremely varying demand. Comparing the solutions approaches, it can be concluded that when applying Lagrangean relaxation algorithm to the presented MILP model, the derived quantities present small variance than the solutions derived from the solution of the MILP model. Due to the fact that demand of fuelwood is not constant, but uncertain, scenarios are used to model the increase or the decrease in fuelwood demand. Thus if a rapid increase in demand may occur this will happen with a corresponding probability. If this probability is high then this scenario is more likely to happen, whereas the other scenarios are less likely because their probabilities are complementary. In this case the model will weight all the scenarios according to the occurring probability and the fuelwood quantities that will satisfy all demand scenarios will be produced. As the primary objective of the model is the minimization of the total operational cost, each scenario corresponds to a cost which in turn is integrated through probabilities to the overall expected cost. For the two sets of probabilities tested, it can be concluded that extreme fuelwood demand can eventually increase more the expected cost than the conservative increase in demand.

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